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Color-Magnitude Diagrams of Merged Globular Clusters: Metallicity Effects

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ABSTRACT

Mergers of globular clusters (GCs) once associated with dwarf spheroidal (dSph) galaxies have recently been suggested as an explanation for the bimodal horizontal branches (HBs) of some Galactic GCs, most notably NGC 1851, NGC 2808, and NGC 6229. Through analysis of the available color-magnitude diagrams for the GCs in the Fornax and Sagittarius dSph satellites of the Milky Way, as well as their metallicity distributions, we argue that the merger of two GCs would most likely produce a bimodal distribution in red giant branch (RGB) colors, or at least a significant broadening of the RGB, due to the expected difference in metallicity between the two merging globulars. No GC with a bimodal RGB is currently known, and the tightness of the RGB sequences in the above bimodal-HB GCs implies that a merger origin for their HB bimodality is unlikely.

Subject headings: Stars: Hertzsprung-Russell (HR) diagram — Stars: Horizontal-Branch — Stars: Population II — Globular Clusters: General — Galaxies: Local Group — Galaxies: Star Clusters.

1. Introduction

The second-parameter phenomenon is a very intriguing anomaly affecting the color-magnitude diagrams (CMDs) of Galactic globular clusters (GCs). The morphology of the horizontal branch (HB) is observed to be primarily a function of the metallicity $[\mathrm{Fe/H}] = \log(\mathrm{Fe/H})_{\mathrm{GC}} - \log(\mathrm{Fe/H})_{\odot}$, the "first parameter." However, superimposed on this main trend one finds intrinsic scatter, caused by cluster-to-cluster variations in some unknown "second parameter" (Sandage & Wallerstein 1960; Sandage & Wildey 1967; van den Bergh 1967).

The idea that age is the second parameter has been very popular, but evidence has been mounting suggesting a much more complex scheme where several parameters may be simultaneously playing more or less important rôles (see Stetson, VandenBerg, & Bolte 1996 and Fusi Pecci & Bellazzini 1997 for recent reviews). One of the strongest arguments against age as the "only" second parameter is provided by the remarkable existence of the second-parameter effect within *individual* GCs (Rood et al. 1993), such as NGC 1851, NGC 2808, and NGC 6229 (Walker 1992b; Ferraro et al. 1990; Borissova et al. 1997). Since all stars within any individual GC presumably have the same age, a different second parameter must be responsible for the existence of both red and blue HBs within the same cluster.

In a recent paper, van den Bergh (1996, hereafter VDB96) has tentatively proposed that this argument against age as the second parameter may be incorrect. In his new scenario, the merger between two GCs of different HB morphologies within dwarf spheroidal galaxies (dSph's) such as Fornax or Sagittarius could lead to bimodal HB types without violating the idea that age is the second parameter. Thus, the bimodal-HB clusters could have originated in mergers between second-parameter pairs of GCs in dSph's that were subsequently accreted by our Galaxy, as envisaged by Searle & Zinn (1978).

As noted by VDB96, the merger of two GCs could affect not only the HB morphology but also other aspects of the CMD. The purpose of this *Letter* is to examine the implications of the merger scenario for the morphology of the CMD, especially in the red giant branch (RGB) region. We begin in the following section by presenting CMDs produced by "merging" GCs in the Sagittarius and Fornax dSph's and in the LMC. We argue that these merged CMDs are not consistent with the tight RGBs observed in Galactic GCs. In Sect. 3 we discuss the metallicity dispersions that one would expect within merged clusters. Finally, in Sect. 4 we summarize our results.

2. Testing the Merger Hypothesis: GCs in Sagittarius, Fornax, and the LMC

2.1. GCs in the Sagittarius dSph

As an example in support of the merger hypothesis, VDB96 has pointed out that a merger involving the GCs Arp 2 (blue HB) and Terzan 7 (red HB) would lead to a bimodal HB. These two GCs, along with Terzan 8 and M54 (NGC 6715), are associated with the Sagittarius dSph

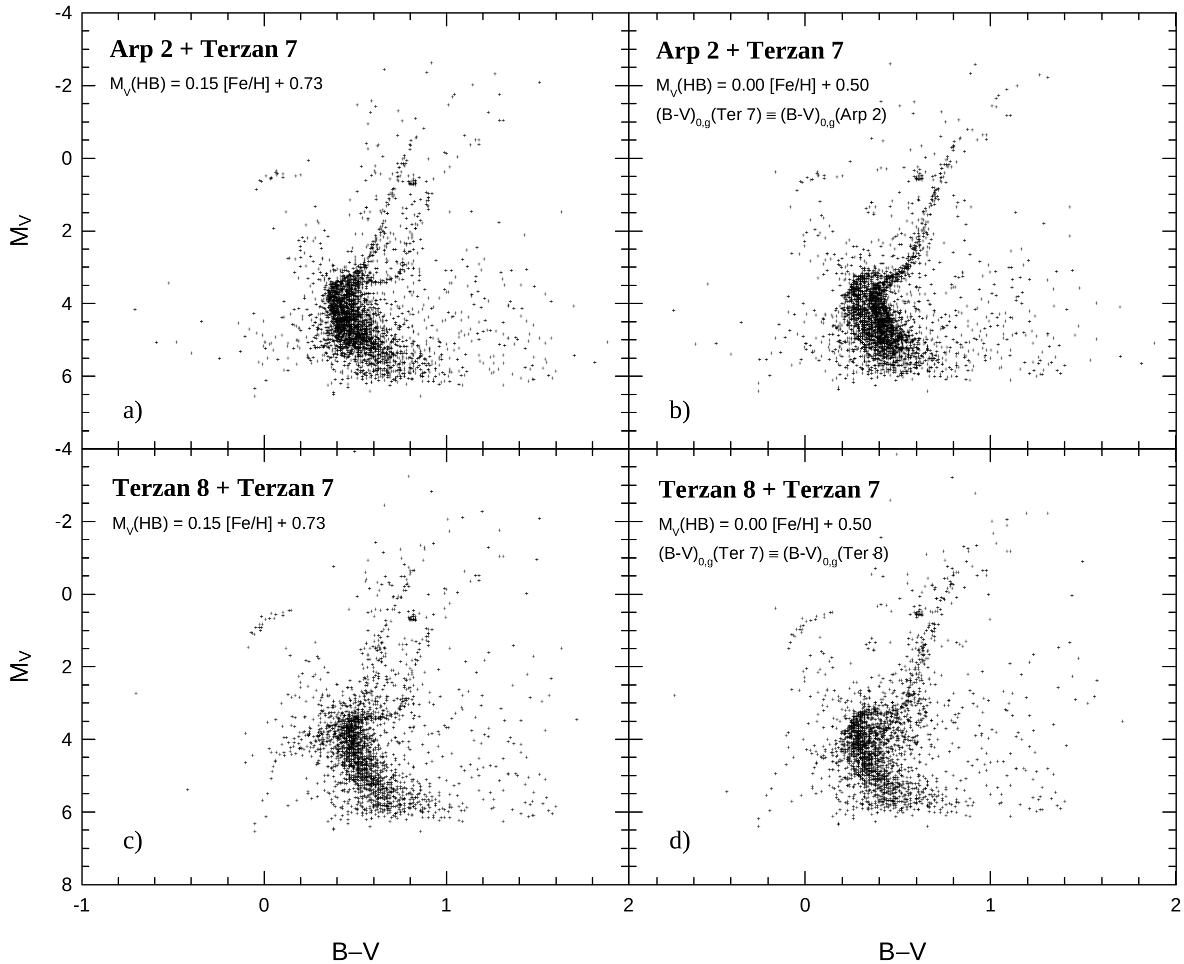

Fig. 1.— Simulation of a "merger" between Arp 2 and Ter 7 (panel a) and between Ter 8 and Ter 7 (panel c) in the Sagittarius dSph. Panels b and d are analogous to panels a and b, except that a match is forced between the colors of the two RGBs at the HB luminosity level. The adopted $M_V(\mathrm{HB})$ – [Fe/H] relations are also shown in the upper left-hand corners.

(Ibata, Gilmore, & Irwin 1995; Da Costa & Armandroff 1995; but see Velázquez & White 1995).

In Fig. 1a, we combine the CMDs of Arp 2 and Ter 7 (Buonanno et al. 1995a,b) to schematically illustrate the implications of a merger between these two clusters. The colors and magnitudes were corrected for reddening according to the $E(B-V)$ values provided by Harris (1996), and the distance modulus determined adopting Walker's (1992a) distance scale. The choice of alternative distance scales does not change the conclusions of this *Letter*.

The most remarkable feature of the CMD shown in Fig. 1a, besides the bimodal HB, is the clearly bimodal RGB. This is due to the metallicity difference between these two clusters (e.g., Buonanno et al. 1995a,b): Ter 7 has a substantially redder RGB than does Arp 2, which is ≈ 1 dex more metal-poor. In fact, inspection of Fig. 1a reveals that almost the whole combined CMD

presents signs of bimodality. Such a clearly bimodal RGB distribution has never, to the best of our knowledge, been observed in a GC.

In Fig. 1b, we arbitrarily “slide” the Ter 7 CMD by 0.20 mag in $B-V$, so as to match the Arp 2 RGB color at the HB level. The two HBs are also aligned in brightness. As expected, the RGB bimodality has been substantially diminished, though not entirely—especially on the upper RGB. The bimodality in the subgiant branch and in the turnoff and main sequence are even more evident than in Fig. 1a. Note that, in producing Fig. 1b, we have effectively assumed that the Ter 7 reddening value listed by Harris (1996), $E(B-V) = 0.06$ mag, is too small by 0.2 mag. This, however, can be safely ruled out (Buonanno et al. 1995b).

In Figs. 1c and 1d, we repeat the above experiment, but replacing Arp 2 with Ter 8 (Ortolani & Gratton 1990; Ortolani 1996). The situation is clearly analogous to the Arp 2 plus Ter 7 case. The HB bimodality is again accompanied by a very peculiar bimodal RGB.

An experiment involving the cluster M54 has not been possible, due to the multiple nature of the CMD in the direction of this cluster, caused (at least in part) by contamination by Sagittarius field stars (Sarajedini & Layden 1995). However, since this cluster too is more metal-poor than Ter 7, we predict that a merger between M54 and Ter 7 would also lead to a bimodal RGB, although the large mass difference between the two clusters would make Ter 7’s contribution to a combined CMD appear little more than a secondary contamination. It should be interesting to note, at any rate, that the composite nature of M54’s CMD *may* be consistent with a merger event.

2.2. GCs in the Fornax dSph

The only other dSph associated with the Galaxy known to contain GCs is Fornax, which has an anomalously high specific frequency of GCs (Fusi Pecci 1987). Since Fornax is more distant, the CMDs for its GCs are not as well defined as in Sagittarius. Fortunately, however, the new Buonanno et al. (1996, hereafter BCFFPB96) data allow us to present preliminary simulations of the “merger” between pairs of GCs in that remote dSph.

Fig. 1 in BCFFPB96 shows that Cluster 4 is possibly the only one with a predominantly red HB in Fornax. The remaining GCs seem to have either intermediate or predominantly blue HB types (see also Beauchamp et al. 1995). The “merger” between clusters 1 and 4 in Fornax is illustrated in Fig. 2a. In Fig. 2b, a similar “merger” experiment involving clusters 3 and 4 is shown. Despite the relatively poorly defined CMDs, the bimodality in the upper RGBs is still quite evident.

VDB96 argues that Fornax clusters 1 and 2 may have narrowly missed a merging event in the past. Even though a CMD for Cluster 2 is not available for a straightforward comparison with the Cluster 1 CMD of BCFFPB96, the nominal metallicity difference between the two clusters, $\simeq 0.19$ dex (Buonanno et al. 1985; Dubath, Meylan, & Mayor 1992), if real, would again show up as a

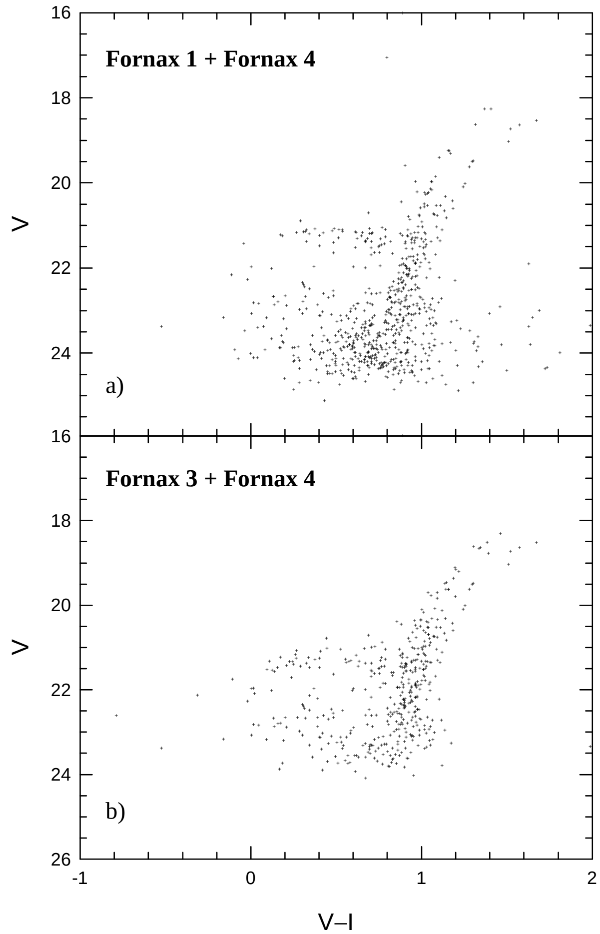

Fig. 2.— Same as Fig. 1, but for clusters 1 and 4 (panel a) and clusters 3 and 4 (panel b) in the Fornax dSph. The data were obtained from BCFFPB96. As in that study, we have restricted the CMD of Cluster 3 (NGC 1049) to stars in the core of the cluster, and the CMD of Cluster 4 to an annulus around the cluster center (cf. their Figs 1d and 1f, respectively).

bimodality in the merger's RGB, if and when the merger product were finally captured by the Galaxy.

2.3. GCs in the LMC

It has been suggested that some of the ancestral fragments that led to the formation of the Galaxy in the Searle & Zinn (1978) scenario were actually significantly more massive than the dSph's, perhaps resembling more closely the LMC in this respect (van den Bergh 1993). Indeed, some of the Galactic GCs may have been stripped from the Magellanic Clouds (van den Bergh 1994). Thus, we have also examined the Pop. II GCs in the LMC (Suntzeff et al. 1992) in connection with the VDB96 hypothesis.

Since none of the Pop. II GCs in the LMC has a red HB, no pair of GCs whose merger would clearly lead to a bimodal HB could be found. Interestingly, mergers of *young* GCs do seem to be currently taking place in the LMC. However, these merging GCs were probably formed simultaneously within the same protocluster cloud, implying that the involved pairs of GCs have essentially the same ages and chemical composition (Bhatia et al. 1991; Bica, Clariá, & Dottori 1992; Rodrigues et al. 1994). An exception seems to be provided by the pair NGC 1938/NGC 1939, where the difference in age may be higher than 5 Gyr (Bica et al. 1992). Apart from this case, no sign of bimodality would be currently present in the corresponding CMDs as a direct result of the mergers, if these had taken place several Gyr ago. However, we speculate that an indirect influence *might* result due to the possible impact of the merger on the intracluster distribution in stellar rotational velocities and mass loss rates.

3. Metallicity Distributions

In the previous section, we have found that the mergers of GCs tend to produce bimodal RGB distributions. The reason for this, as already discussed, is the difference in metallicity between the merging GCs. That the RGB color should become redder with increasing metallicity has been known observationally since Sandage & Wallerstein (1960) and Wildey (1961). The effect is also well understood theoretically (Hoyle & Schwarzschild 1955). Moreover, the shape of the RGB also depends strongly on [Fe/H], as recently discussed by Da Costa & Armandroff (1990) and Ortolani, Barbuy, & Bica (1991).

Two questions arise from this: how tightly is the [Fe/H] dispersion constrained within *single* GCs, especially those with bimodal HBs? And what is the expected dispersion in [Fe/H] in the merger scenario, given the observed metallicity dispersion of the GC systems in the dSph galaxies?

As to the first question, it is important to note that current upper limits on the metallicity dispersions within individual GCs are *extremely* tight. In fact, as stated by Suntzeff (1993), "0.04 dex is a realistic upper limit to the average cluster metallicity inhomogeneity." Part of the reason for this remarkable accuracy is exactly the fact that the RGB color and shape depend so sensitively on [Fe/H]. As far as the *bimodal-HB clusters* are concerned, NGC 1851 has been studied by Da Costa & Armandroff (1990). According to their analysis, the 3σ upper limit on the internal metallicity dispersion is 0.07 dex. The CMD study of NGC 2808 by Fusi Pecci & Ferraro (1996) similarly implies a 3σ upper limit of ≈ 0.15 dex for the dispersion in [Fe/H] within the cluster. For NGC 6229, Borissova et al. (1997) have estimated that the width of the RGB is essentially consistent with their measurement errors, implying no intrinsic dispersion in [Fe/H] within the cluster. In fact, among all the GCs for which CMDs are available, ωCen (NGC 5139), M22 (NGC 6656), M92 (NGC 6341), and M54 (in Sagittarius) are the only cases for which an internal metallicity dispersion has been proven or suspected (Suntzeff 1993 and references therein; Sarajedini & Layden 1995).

Using the latest metallicity and CMD data available in the literature, we have performed a detailed analysis of the [Fe/H] and HB morphology distributions of the GCs in the Fornax and Sagittarius dSph's, as well as in the LMC and in the Fusi Pecci et al. (1995) groups of GCs that may have shared a possible common origin within a Searle & Zinn (1978) "building block" of the Galaxy (see also Lynden-Bell & Lynden-Bell 1995). Our results indicate that *a general prediction of the merger hypothesis is that many mergers involving pairs of globulars with different metallicities would be expected for every merger involving a pair of GCs with different HB morphology but essentially the same metallicity.* By "different metallicities" is meant Δ[Fe/H] > 0.04 dex (Suntzeff 1993). Searle (1977) has also pointed out that a merger might lead to an inhomogeneous, and possibly bimodal, metallicity distribution. In fact, a bimodal HB would be much more likely to result from the merger between two GCs of different metallicities than between two clusters of nearly the same metallicity. This is simply a consequence of the fact that metallicity is the *first* parameter. At the same time, bimodal RGBs are a much more natural consequence of the mergers of GCs than are bimodal HBs, since *the impact of even tiny differences in [Fe/H] on stellar colors are greatly amplified during the RGB phase.*

These conclusions are also supported by an analysis of the GC metallicity distribution in NGC 147, NGC 185, and (to a lesser extent) NGC 205—the dSph companions to M31 known to contain GCs (see, e.g., Minniti, Meylan, & Kissler-Patig 1996); and by the metallicity distributions in the M31 GC "groups" proposed by Ashman & Bird (1993).

4. Conclusions

The above analysis indicates that, in all likelihood, mergers of GCs cannot have been responsible for the HB bimodality in NGC 1851, NGC 2808, and NGC 6229, since the size of the metallicity dispersion within these clusters is very tightly constrained, as opposed to what would be expected in the merger scenario. Moreover, bimodal RGBs and RGBs which are substantially wider than those which are usually observed would be much more frequent in the Galactic GC system as a whole, if mergers of bona-fide old GCs were responsible for the existence of bimodal-HB clusters. We suggest that signs of merger events between old GCs should be searched for primarily in the RGB region of the CMD, where even small metallicity differences between the merging globulars are expected to greatly affect the resulting distributions.

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